AFCRC-TN-179
ASTIA DOCUMENT No. AD117007

EM-102

NEW YORK UNIVERSITY
Institute of Mathematical Sciences
Division of Electromagnetic Research

RESEARCH REPORT No. EM-102

Propagation of Electromagnetic Pulses Around the Earth

BERTRAM R. LEVY and JOSEPH B. KELLER

CONTRACT No. AF 19(604)1717
FEBRUARY, 1957

EM-102

NEW YORK UNIVERSITY

Institute of Mathematical Sciences
Division of Electromagnetic Research

Research Report No. EM-102

PROPAGATION OF ELECTROMAGNETIC PULSES AROUND THE EARTH

Bertram R. Levy and Joseph B. Keller

Bertram R. Levy
Bertram R. Levy

Joseph B. Keller
Joseph B. Keller

Morris Kline
Morris Kline
Project Director

February, 1957

The research reported in this document has been sponsored by the Air Force Cambridge Research Center, Air Research and Development Command, under Contract No. AF 19(604)1717.

New York, 1957

Abstract

The propagation of electromagnetic pulses around the earth is investigated analytically. The pulses are assumed to be produced by a vertical electric or magnetic dipole. The earth is treated as a homogeneous sphere of either finite or infinite conductivity and the atmosphere is assumed to be homogeneous. It is found that very short pulses become longer the further they propagate, in addition to diminishing in amplitude. The duration of a pulse which is initially a delta-function increases as θ^3, where θ is the angle between source and receiver. The results are represented as products of several factors, which we call the amplitude factor, the pulse-shape factor, the time-dependent height-gain factor for the source and receiver, and the conductivity factor. Graphs of these factors and of the pulse shape for several cases are given.

Table of Contents

1. Introduction

Suppose an electromagnetic pulse of given shape and amplitude is emitted by a source on or near the ground. We wish to find its shape, amplitude and arrival time at any point beyond the horizon on or near the ground. In particular we wish to determine the effects of the ground conductivity along the propagation path. We will assume that the source is a vertical dipole of either electric or magnetic type and that the earth is a homogeneous sphere. By a slight modification of our procedure, we could also treat the case in which the ground conductivity varies along the propagation path.

The method of solution consists of two steps. First we must obtain the Hertz vector which represents the field due to a time harmonic or periodic source. Then by Fourier superposition of these periodic fields we can obtain the Hertz vector for a delta-function source. Other pulse-type sources can be treated by superposition of delta-function fields.

Since the field due to a periodic source has been determined by numerous authors, our first step is simple--we need merely copy the Hertz vector of this field. This is done in Section 2, the books of V.A. Fock[1] and H. Bremmer[2] being used as sources. In Section 3 we write the Fourier integral representing the Hertz vector of the field due to a delta-function source. We then evaluate this integral by the saddle point method and obtain a simple formula as the result for each type of dipole. In Section 4 some graphs based on these formulas and a discussion of the results are given.

We wish to acknowledge our indebtedness to Prof. Bernard Friedman who previously analyzed the field due to a pulsed line source near a perfectly conducting cylinder.

2. The field of a periodic source

Suppose a vertical electric dipole is located at the point $r = \rho$, $\theta = 0$ of a polar coordinate system with the origin at the center of the earth. Then its field can be expressed in terms of a Hertz vector having only a radial component $rU_e(r,\theta,t)$, by the formulas

$$(1) \qquad E = \nabla \times \nabla \times (\vec{r}U_e)$$

$$H = (\varepsilon \frac{\partial}{\partial t} + \sigma) \nabla \times (\vec{r}U_e).$$

Similarly, the field of a vertical magnetic dipole at $r = \rho$, $\theta = 0$ can be expressed in terms of a radial Hertz vector $rU_m(r,\theta,t)$ by the formulas

The numbers τ_s^∞ and τ_s^o are complex, lying on the ray arg $\tau = \pi/3$. The τ's of smallest absolute value are

$$(16) \qquad \tau_o^\infty = 0.808\, e^{i\pi/3}$$

$$(17) \qquad \tau_o^o = 1.856\, e^{i\pi/3}.$$

For a highly conducting earth σ_1 is large so δ_e is large and δ_m is small. Therefore the series (14) is useful for computing τ_s in the electric case and (15) is useful in the magnetic case. For the same reason (8) is more convenient for computing f in the electric case, and (9) is in the magnetic case.

3. <u>The field of a delta-function source</u>

The Hertz potential $U(r,\theta,t)$ of the field due to a vertical electric or magnetic dipole having any time dependence can be obtained by Fourier superposition of the periodic potentials $u(r,\theta)e^{-i\omega t}$ described above. Since $k = \omega/c$, where $1/c = \sqrt{\varepsilon\mu}$, we can integrate with respect to k instead of ω and obtain

$$(18) \qquad U(r,\theta,t) = \frac{c}{2\pi} \int_{-\infty}^{\infty} A(k)u(r,\theta)e^{-ikct}\, dk.$$

In (18) the Fourier amplitude $A(k)$ is determined by the time dependence and amplitude of the source. With the function $u(r,\theta)$ defined as in the preceding section, a delta-function source has the amplitude $A(k) \equiv 1$. In the absence of the earth, the Hertz potential of the field due to such a dipole would be

$$(19) \qquad U_o = \frac{\delta(t - \frac{R}{c})}{4\pi R}.$$

Here $R = (r^2 + \rho^2 - 2\rho r \cos\theta)^{1/2}$ is the distance from the source to the receiver. Thus with $A(k) \equiv 1$, (18) will yield the diffracted pulse due to the incident pulse (19).

To evaluate (18) we introduce the time T defined by

$$(20) \qquad T = t - \frac{a\theta}{c} + \frac{a}{c}\cos^{-1}\left(\frac{a}{\rho}\right) + \frac{a}{c}\cos^{-1}\left(\frac{a}{r}\right).$$

This time T is just the time measured from the arrival of the diffracted wave front at the point (r,θ), assuming that the source starts at $t = 0$. We now insert (8)

or (9) into (18) and set $A(k) = 1$.

Let us first consider the case of a perfectly conducting earth. In this case τ is independent of k and δ is either infinity or zero. Then for $T < 0$ the contour in (18) can be closed in the upper half-plane to yield the value zero for U. This is, of course, to be expected from the definition of T. For $T > 0$ we evaluate (18) by the saddle point method. In the electric case we use (8) in (18), set $\delta_e = \infty$ and obtain

$$(21) \quad U_e(r,\theta,t) = \sum_s \frac{c\theta}{2^{5/2}\, 3^{1/2}\, \pi\, a^{1/2}\, |\tau_s^\infty|^{1/2} (\sin\theta)^{1/2}} \cdot \frac{1}{(cT)^{3/2}} \exp\left[- \frac{2}{3^{3/2}} \frac{|\tau_s^\infty|^{3/2}\, \theta^{3/2}\, a^{1/2}}{(cT)^{1/2}} \right] \cdot \frac{v\left\{|\tau_s^\infty|\, 2^{1/3}\left(\frac{\theta(r-a)}{3cT} - 1\right)\right\}}{v(-|\tau_s^\infty| 2^{1/3})} \; \frac{v\left\{|\tau_s^\infty| 2^{1/3}\left(\frac{\theta(\rho-a)}{3cT} - 1\right)\right\}}{v(-|\tau_s^\infty| 2^{1/3})} .$$

In the magnetic case we use (9) in (18), set $\delta_m = 0$ and obtain

$$(22) \quad U_m(r,\theta,t) = \sum_s \frac{c\theta\, |\tau_s^o|^{1/2}}{2^{5/2}\, 2^{1/3}\, 3^{1/2}\, \pi a^{1/2}\, (\sin\theta)^{1/2}} \cdot \frac{1}{(cT)^{3/2}} \exp\left[- \frac{2}{3^{3/2}} \frac{|\tau_s^o|^{3/2}\, \theta^{3/2}\, a^{1/2}}{(cT)^{1/2}} \right] \cdot \frac{v\left\{|\tau_s^o| 2^{1/3}\left(\frac{\theta(r-a)}{3cT} - 1\right)\right\}}{v'(-2^{1/3}\, |\tau_s^o|)} \; \frac{v\left\{|\tau_s^o| 2^{1/3}\left(\frac{\theta(\rho-a)}{3cT} - 1\right)\right\}}{v'(-2^{1/3}\, |\tau_s^o|)} .$$

The function v in (21) and (22) is the imaginary part of the Airy function, $v = \operatorname{Im} w$. For large positive z, v(z) is asymptotic to $\frac{1}{2} z^{-1/4} \exp\left[- \frac{2}{3} z^{3/2}\right]$ while for large negative z, v(z) is asymptotic to $(-z)^{-1/4} \sin\left[\frac{2}{3}(-z)^{3/2} + \frac{\pi}{4}\right]$. In the intermediate region the values of v(z) have been tabulated by V. A. Fock [1].

Now let us consider the case of a finitely conducting earth. In the

electric case we will use for τ_s the first two terms of (14) with $\delta = \delta_e$. Upon inserting (8) into (18), with this value of τ_s, and putting $A(k) = 1$, we obtain an expression for $U_e(r,\theta,t)$. For $T < 0$ this expression is zero, as before. For $T > 0$ we again use the saddle point method. Since δ_e is a function of k, the determination of the saddle point is more complicated than in the previous cases. Therefore we neglect the term $-1/(2\tau_s^\infty \delta_e)$ compared with τ_s^∞ in determining the saddle point. Then we obtain

$$(23)\quad U_e(r,\theta,t) = \sum_s \frac{c\theta\,|\tau_s^\infty|^{1/2}}{2^{3/2}\,3^{1/2}\,\pi a^{1/2}(\sin\theta)^{1/2}} \cdot \frac{1}{2|\tau_s^\infty| + \dfrac{1}{|\tau_s^\infty||\delta_e^*|}}$$

$$\cdot \frac{1}{(cT)^{3/2}} \exp\left[-\frac{2}{3^{3/2}} \frac{\left[|\tau_s^\infty| + \dfrac{1}{2|\tau_s^\infty|}\cdot\dfrac{1}{|\delta_e^*|}\right]^{3/2} \theta^{3/2}\, a^{1/2}}{(cT)^{1/2}}\right]$$

$$\cdot \frac{v\left\{|\tau_s^\infty|\, 2^{1/3}\left(\dfrac{\theta(r-a)}{3cT} - 1\right)\right\}}{v(-|\tau_s^\infty|\, 2^{1/3})} \; \frac{v\left\{|\tau_s^\infty|\, 2^{1/3}\left(\dfrac{\theta(\rho-a)}{3cT}\right) - 1\right\}}{v(-|\tau_s^\infty|\, 2^{1/3})}\,.$$

In (23), δ_e^* is the value of δ_e at the stationary point. Its absolute value is given by

$$(24)\quad |\delta_e^*| = \left(\frac{3\,T}{|\tau_s^\infty|\,T_2}\right)^{1/2} \frac{\dfrac{\varepsilon_1}{\varepsilon} + \dfrac{3^{3/2}\sigma_1\mu c a}{|\tau_s^\infty|^{3/2}}\left(\dfrac{T}{T_2}\right)^{3/2}}{\sqrt{\dfrac{\varepsilon_1}{\varepsilon} - 1 + \dfrac{3^{3/2}\sigma_1\,\mu c a}{|\tau_s^\infty|^{3/2}}\left(\dfrac{T}{T_2}\right)^{3/2}}}\,.$$

Here $T_2 = \theta a/c$ is the travel time for the pulse to reach the point θ from the source at $\theta = 0$.

In the magnetic case we use the first two terms in (15) for τ_s with $\delta = \delta_m$. Then using (9) in (18) with $A(k) = 1$ we obtain an expression for $U_m(r,\theta,t)$. As before this expression is zero for $T < 0$, while for $T > 0$ we obtain

$$(25)\quad U_m(r,\theta,t) = \sum_s \frac{c\theta|\tau_s^0|^{1/2}}{2^{5/2}\,2^{1/3}\,3^{1/2}\,\pi a^{1/2}(\sin\theta)^{1/2}} \; \frac{1}{2|\delta_m|^2(|\tau_s^0| - |\delta_m^*|) + 1}$$

$$\cdot \frac{1}{(cT)^{3/2}} \exp\left[-\frac{2}{3^{3/2}} \frac{\left[|\tau_s^0| - |\delta_m^*|\right]^{3/2} \theta^{3/2}\, a^{1/2}}{(cT)^{3/2}}\right]$$

$$\cdot \frac{v\left\{|\tau_s^o| 2^{1/3}\left(\frac{\theta(\rho-a)}{3cT}-1\right)\right\}}{v'(-2^{1/3}|\tau_s^o|)} \frac{v\left\{|\tau_s^o| 2^{1/3}\left(\frac{\theta(r-a)}{3cT}-1\right)\right\}}{v'(-2^{1/3}|\tau_s^o|)} .$$

Here δ_m^* is the value of δ_m at the stationary point and $|\delta_m^*|$ is given by

$$(26) \qquad |\delta_m^*| = \left(\frac{3cT}{|\tau_s^o|\theta a}\right)^{1/2} \frac{1}{\sqrt{\frac{\varepsilon_1}{\varepsilon} - 1 + \frac{\sigma \mu c \, 3^{3/2} \, (cT)^{3/2}}{|\tau_s^o|^{3/2} \, a^{1/2} \, \theta^{3/2}}}} .$$

4. Discussion of results

We have calculated the Hertz vector of the field due to a vertical electric or magnetic dipole with a delta function time dependence. For a perfectly conducting earth we obtain (21) and (22), while for finite conductivity we obtain (23) and (25). Of course (23) reduces to (21) and (25) to (22) as $\sigma_1 \to \infty$. These results are useful at points beyond the horizon and therefore only the first term ($s = 0$) in each result need be retained. This is so because the other terms have relatively rapidly decaying exponential factors. Consequently our results are rather simple formulas.

Let us examine $U_e(r,\theta,t)$ for the perfectly conducting case when both the source and observation point are on the ground ($\rho = a$ and $r = a$). Then (21) becomes

$$(27) \quad U_e(a,\theta,t) = A_e(\theta) \, S(T/T_{eo}).$$

Here the amplitude $A_e(\theta)$ is the maximum value of U_e, the build-up time $T_{eo}(\theta)$ is the time at which the maximum occurs and $S(T/T_{eo})$ is the pulse shape factor. A, T_{eo} and S are given by

$$(28) \quad A_e = \frac{3^7 c}{|\tau_o^{\infty}|^5 \, 2^{11/2} \, \pi e^3 a^2} \frac{1}{\sqrt{\theta^7 \sin\theta}} = (1.64 \times 10^{-5}) \frac{1}{\sqrt{\theta^7 \sin\theta}} \sim (1.64 \times 10^{-5}) \frac{1}{\theta^4} ,$$

$$(29) \qquad T_{eo} = \frac{4|\tau_o^{\infty}|^3 a}{3^5 c} \; \theta^3 = (1.85 \times 10^{-4}) \, \theta^3 ,$$

$$(30) \qquad S(T/T_{eo}) = (T_{eo}/T)^{3/2} \exp 3\left[1-(T_{eo}/T)^{1/2}\right].$$

A graph of the pulse shape factor S is given in Figure 1. U_e is obtained from this graph by multiplying the vertical side by $A_e(\theta)$, which is given by (28).

If the observation point is above the ground $(r > a)$, U_e is obtained by multiplying (27) by the time dependent height-gain factor $H_e(T/T_{el}(r))$ defined by

$$(31) \qquad H_e\left(\frac{T}{T_{el}(r)}\right) = \frac{v\left[T_{el}(r)/T - 2^{1/3}|\tau_o^{\infty}|\right]}{v\left[-2^{1/3}|\tau_o^{\infty}|\right]} .$$

In (31) the time $T_{el}(r)$ is defined by

$$(32) \qquad T_{el}(r) = 2^{1/3}|\tau_o^{\infty}|\theta(r-a)/3c.$$

A graph of $H_e(T/T_{el}(r))$ is shown in Figure 2. If the source is above the ground $(\rho > a)$ a similar height-gain factor must be introduced. Thus in general we have for the perfectly conducting case

$$(33) \qquad U_e(r,\theta,t) = A_e(\theta)S(T/T_{eo})H_e\big(T/T_{el}(r)\big)H_e\big(T/T_{el}(\rho)\big).$$

A graph of U_e is shown in Figure 3.

If the times $T_{el}(r)$ and $T_{el}(\rho)$ are both small compared to the build up time T_{eo}, both height-gain factors are effectively equal to unity. Then U_e is essentially the same as it is for both source and receiver on the ground. On the other hand if $T_{el}(r)$ and $T_{el}(\rho)$ are large compared to T_{eo}, the maximum of U_e is less than its value for $r = a$, $\rho = a$ by the factor $H_e(T_o/T_{el}(r))H_e(T_o/T_e(\rho))$. In this case the shape of the pulse is also slightly altered.

In case of finite conductivity, (23) shows that U_e is obtained by multiplying (33) by the conductivity factor $C_e(T/T_{eo},T/T_2)$. This factor is given by

$$(34)\qquad C_e = \exp\left[3(T_o/T)^{1/2}\left(1-\left[1+\frac{1}{2|\tau_o^\infty|^2|\delta_e^*|}\right]^{\frac{3}{2}}\right)\right]\cdot\frac{1}{1+\frac{1}{2|\tau_o^\infty|^2|\delta_e^*|}+\frac{1}{2|\tau_o^\infty||\delta_e^*|^2}}.$$

The quantity $|\delta_e^*|$, which depends upon T/T_2 and upon σ_1, is given by (24) with $s = 0$. Thus we have, denoting by U_e^∞ the result (33) for perfect conductivity,

$$(35)\qquad U_e(r,\theta,t) = U_e^\infty(r,\theta,t)\, C_e(T/T_{eo},T/T_2).$$

If we insert the expression (33) for U_e^∞ this becomes

$$(36)\quad U_e(r,\theta,t) = A_e(\theta)S(T/T_{eo})\, H_e(T/T_{e1}(r))\, H_e(T/T_{e1}(\rho))\, C_e(T/T_{eo},\, T/T_2).$$

A graph of C_e is shown in Figure 4 and one of U_e in Figure 5.

A quite similar analysis is also possible in the magnetic case. From (22) we find that the analogue of (33) for U_m in the case of perfect conductivity is

$$(37)\quad U_m(r,\theta,t) = A_m(\theta)\, S(T/T_{mo})\, H_m(T/T_{m1}(r))\, H_m(T/T_{m1}(\rho)).$$

The shape factor S is the same as in the electric case but the amplitude $A_m(\theta)$, the build-up time T_{mo}, the times $T_{m1}(r)$ and $T_{m1}(\rho)$ and the height-gain factors H_m are slightly different. These quantities are given by

$$(38)\quad A_m(\theta) = \frac{3^7 c}{2^{11/2}\, 2^{1/3}\, \pi e^3|\tau_o^o|^4\, a^2}\cdot\frac{1}{\sqrt{\theta^7\sin\theta}} = (3.78\times10^{-3})\frac{1}{\sqrt{\theta^7\sin\theta}} \sim (3.78\times10^{-3})\frac{1}{\theta^4},$$

$$(39)\quad T_{mo} = \frac{4|\tau_o^o|^3\, a}{3^5 c}\,\theta^3 = (2.24\times10^{-9})\,\theta^3,$$

$$(40) \quad T_{m1}(r) = 2^{1/3}|\tau_o^o|\,\theta(r-a)/3c,$$

$$(41) \quad H_m\left(T/T_{m1}(r)\right) = \frac{v\left[T_{m1}(r)/T - 2^{1/3}|\tau_o^o|\right]}{v'\left[-2^{1/3}|\tau_o^o|\right]} .$$

A graph of the height-gain factor H_m is given in Figure 6. This height-gain factor is zero at the ground. Therefore graphs of U_m are given for $r > a$ and $\rho > a$ in Figure 7.

In the case of finite conductivity, we find from (25) that U_m can be obtained by multiplying the result (37) by the conductivity factor $C_m(T/T_{mo},T/T_2)$. This factor is

$$(42) \quad C_m(T/T_{mo},T/T_2) = \frac{\exp\left[3\left(\frac{T_o}{T}\right)^{1/2}\left(1 - \left[1 - \frac{|\delta_m^*|}{|\tau_o^o|}\right]^{3/2}\right)\right]}{2|\delta_m^*|^2\,(|\tau_o^o| - |\delta_m^*|) + 1} .$$

The quantity $|\delta_m^*|$ depends upon T/T_2 and upon σ_1. It is given by (26) with $s = 0$. If we denote the result (37) for perfect conductivity by U_m^∞ we now have

$$(43) \quad U_m(r,\theta,t) = U_m^\infty(r,\theta,t)\; C_m(T/T_{mo},\, T/T_2).$$

If we replace U_m^∞ by means of (37) this becomes

$$(44) \quad U_m(r,\theta,t) = A_m(\theta)\; S(T/T_{mo})\; H_m\left(T/T_{m1}(r)\right) H_m\left(T/T_{m1}(\rho)\right) C_m(T/T_{mo},T/T_2).$$

If $\sigma = 4$ mhos/meter, which is the conductivity of sea water, C_m differs from unity by less than one per cent for all values of θ. Therefore in this case U_m is essentially the same as U_m^∞, which is shown in Figure 7.

The field components can be found from the Hertz vector by equation (1) in the electric case and by equation (21) in the magnetic case. In the electric case $E_\phi \equiv 0$, and $E_\theta = 0$ at $r = a$ in the perfectly conducting case. The main non-zero component of E is E_r. By using (1) and (18) we find, for finite or infinite conductivity, that

$$(45) \quad E_r = -\frac{1}{a}\left[\frac{|\tau_o^\infty|\,T_2}{3T}\right]^3 U_\theta .$$

In the magnetic case $E_r \equiv E_\theta \equiv 0$. From (2) and (18) we find for the only non-zero component of E,

$$(46) \qquad E_\phi = \frac{\mu c}{a} \left[\frac{|\tau_o^o| \, T_2}{3T} \right]^3 U_m .$$

When the source has a time dependence f(t) instead of $\delta(t)$, the result for the Hertz vector or the field components can be obtained from those for the delta function source. If U^f denotes the Hertz vector (electric or magnetic) due to the source f, and U^δ the corresponding Hertz vector due to the delta-function source, then by superposition

$$(47) \qquad U^f(r,\theta,t) = \int_{-\infty}^{\infty} f(\tau)\, U^\delta(r,\theta,t-\tau)\, d\tau .$$

From this equation we see that the minimum resolution time in U^f is the appropriate build-up time T_{eo} or T_{mo}. Thus frequencies higher than $1/T_{eo}$ or $1/T_{mo}$ are essentially lost from the pulse. We may describe this by saying that diffraction has the effect of a low pass filter. This is understandable since high frequency fields do not so readily diffract around the earth.

An alternative to (47), which may be easier to compute from, is

$$(48) \qquad U^f(r,\theta,t) = \bar{f}(ck^*)\, U^\delta\,(r,\theta,t).$$

Here $\bar{f}$ is the Fourier transform of f(t) and k^* is the value of k at the saddle point. It is given by

$$(49) \qquad ck^* = \frac{ic}{a} \left[\frac{|\tau_o| \, T_2}{3T} \right]^{3/2} .$$

Here τ_o is τ_o^∞ in the electric case and τ_o^o in the magnetic case. Although (47) is valid for arbitrary f(t), (48) applies only when f(t) represents a pulse. This limitation results because the phase of $\bar{f}$ was ignored in determining the saddle point.

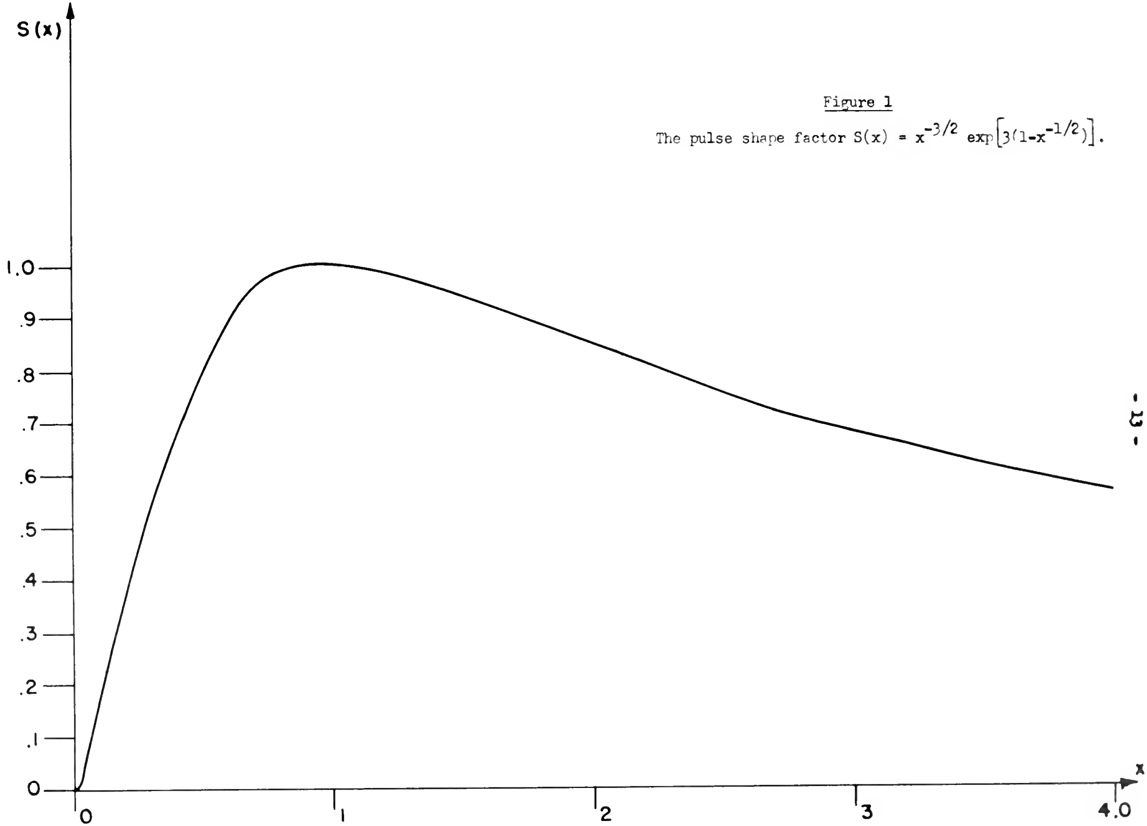
Finally we must point out a limitation on our result (33) in the electric dipole case for a finitely conducting earth. This limitation pertains to small values of T. For such values of T the stationary value of k or ω is large in the integral (18) for U_e. But our approximate calculation of τ_s, which occurs in

that integral, is based on an expansion for large σ and it is not valid when ω is also large. Therefore the result (23) is not accurate for small T. However this range of T is confined to a small interval which terminates long before the maximum occurs, in the case we have considered. No such limitation occurs in the magnetic dipole case, however, since then the expansion for large σ becomes more accurate when ω is large.

References

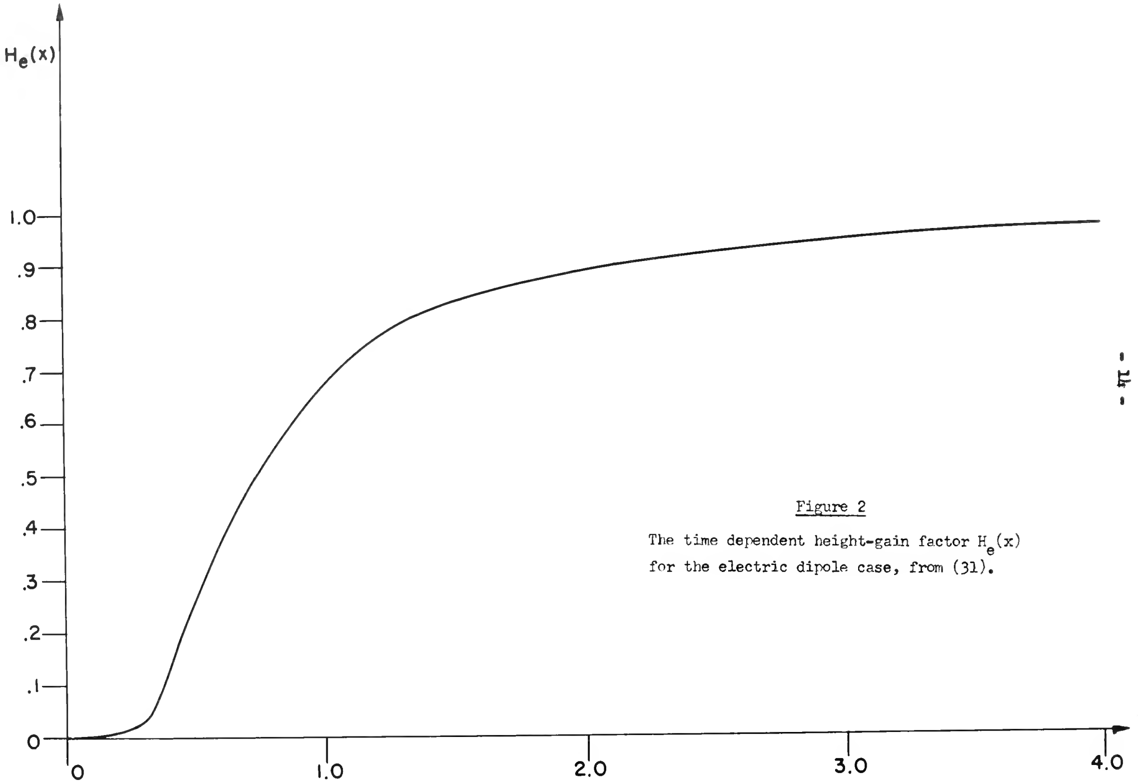
[1] Fock, V.A. - Diffraction of radio waves around the earth's surface; Academy of Sciences, USSR, Moscow, 1946.

[2] Bremmer, H. - Terrestrial Radio Waves, Elsevier, New York, 1949.



<u>Figure 1</u>

The pulse shape factor $S(x) = x^{-3/2} \exp\left[3(1-x^{-1/2})\right]$.



<u>Figure 2</u>

The time dependent height-gain factor $H_e(x)$ for the electric dipole case, from (31).

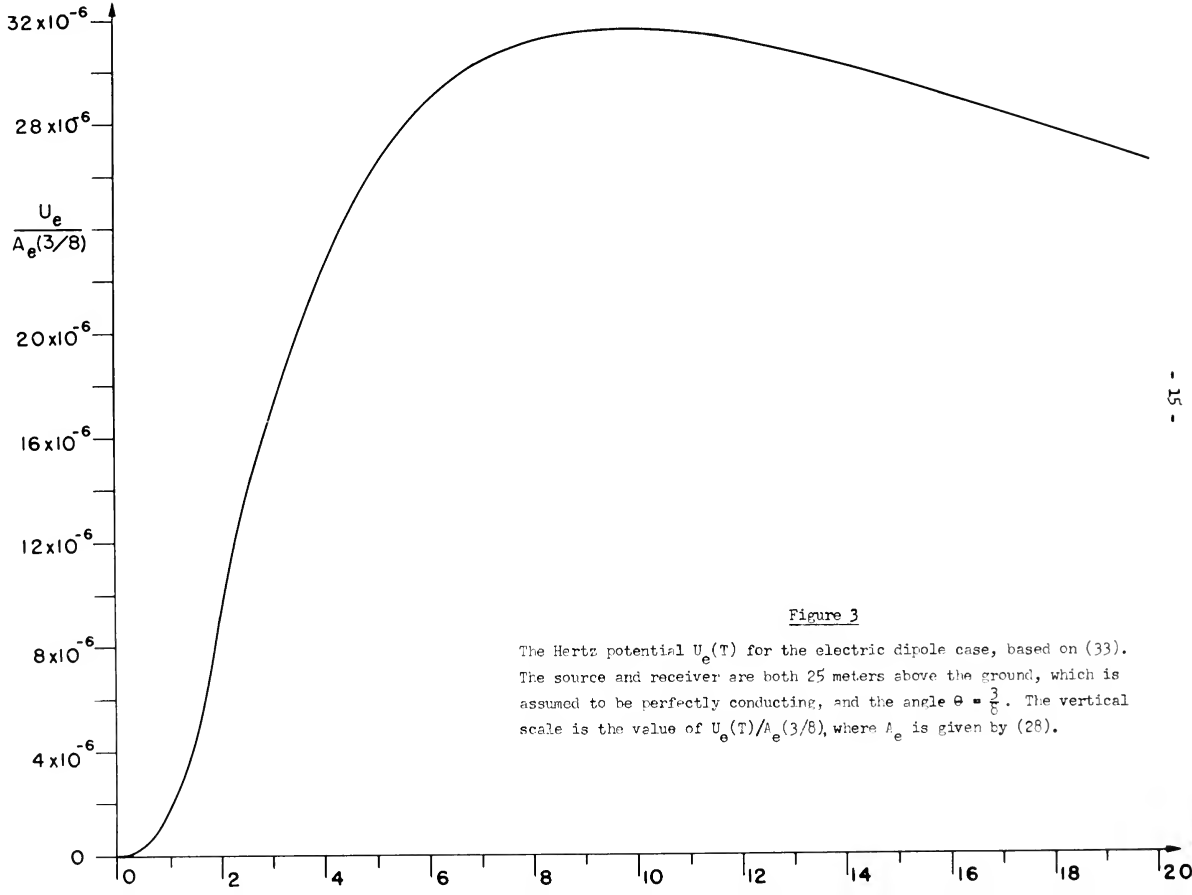


Figure 3

The Hertz potential $U_e(T)$ for the electric dipole case, based on (33). The source and receiver are both 25 meters above the ground, which is assumed to be perfectly conducting, and the angle $\theta = \frac{3}{8}$. The vertical scale is the value of $U_e(T)/A_e(3/8)$, where A_e is given by (28).

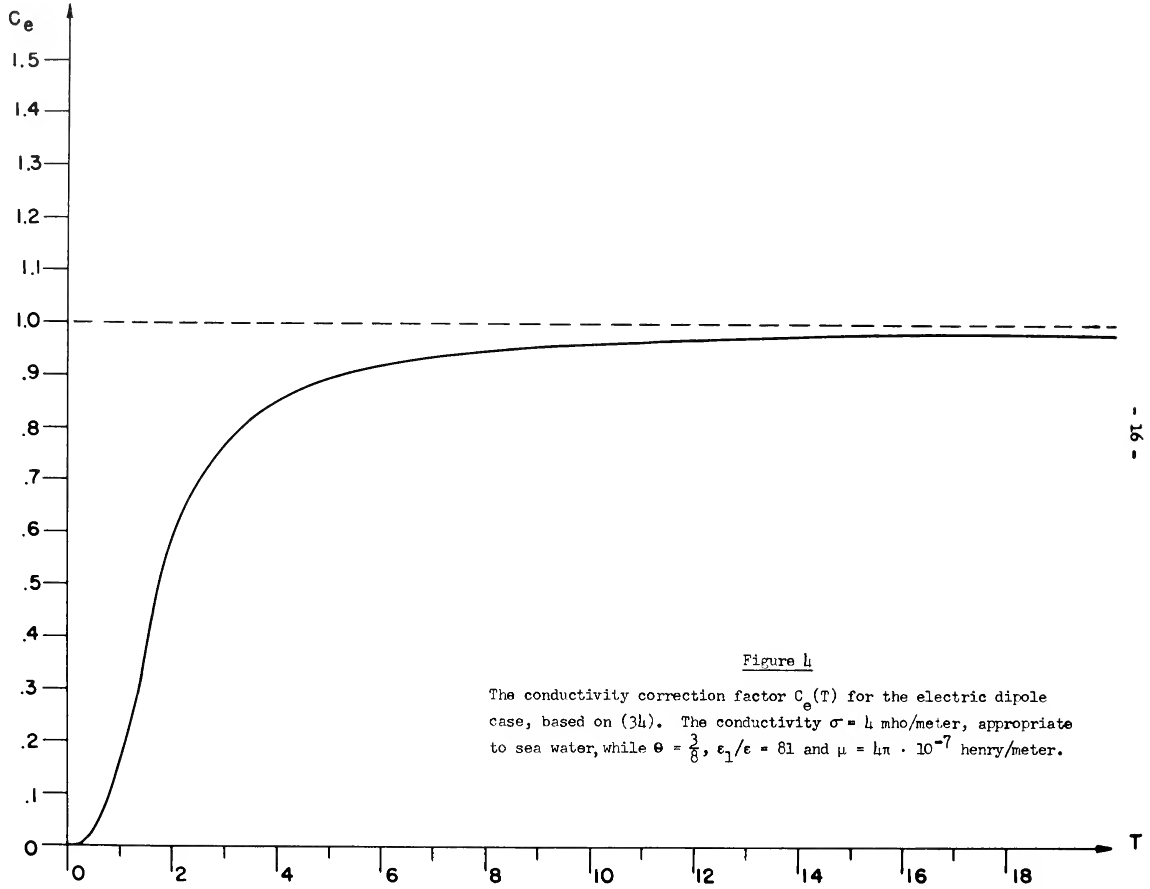


Figure 4

The conductivity correction factor $C_e(T)$ for the electric dipole case, based on (34). The conductivity $\sigma = 4$ mho/meter, appropriate to sea water, while $\theta = \frac{3}{8}$, $\varepsilon_1/\varepsilon = 81$ and $\mu = 4\pi \cdot 10^{-7}$ henry/meter.

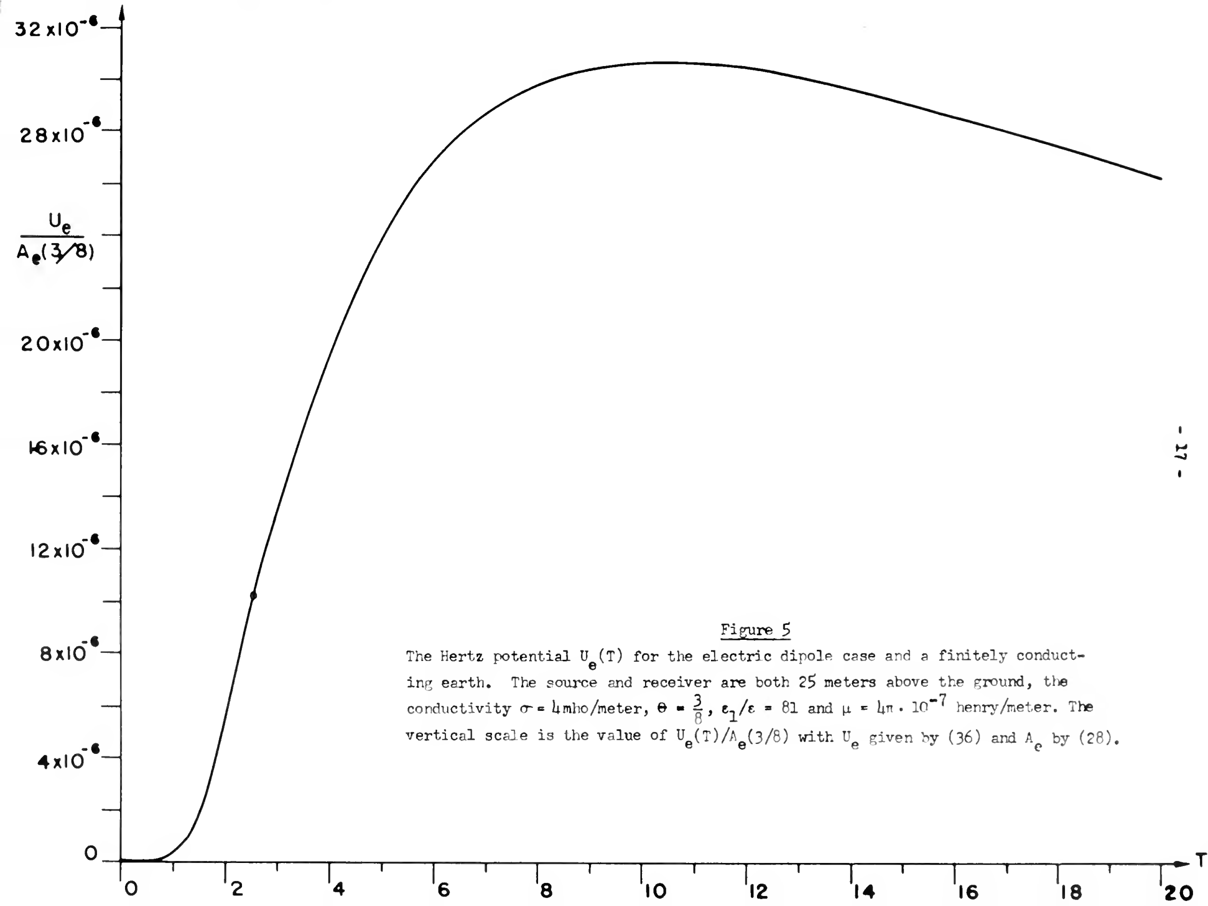


Figure 5

The Hertz potential $U_e(T)$ for the electric dipole case and a finitely conducting earth. The source and receiver are both 25 meters above the ground, the conductivity $\sigma = 4$ mho/meter, $\Theta = \frac{3}{8}$, $\epsilon_1/\epsilon = 81$ and $\mu = 4\pi \cdot 10^{-7}$ henry/meter. The vertical scale is the value of $U_e(T)/A_e(3/8)$ with U_e given by (36) and A_e by (28).

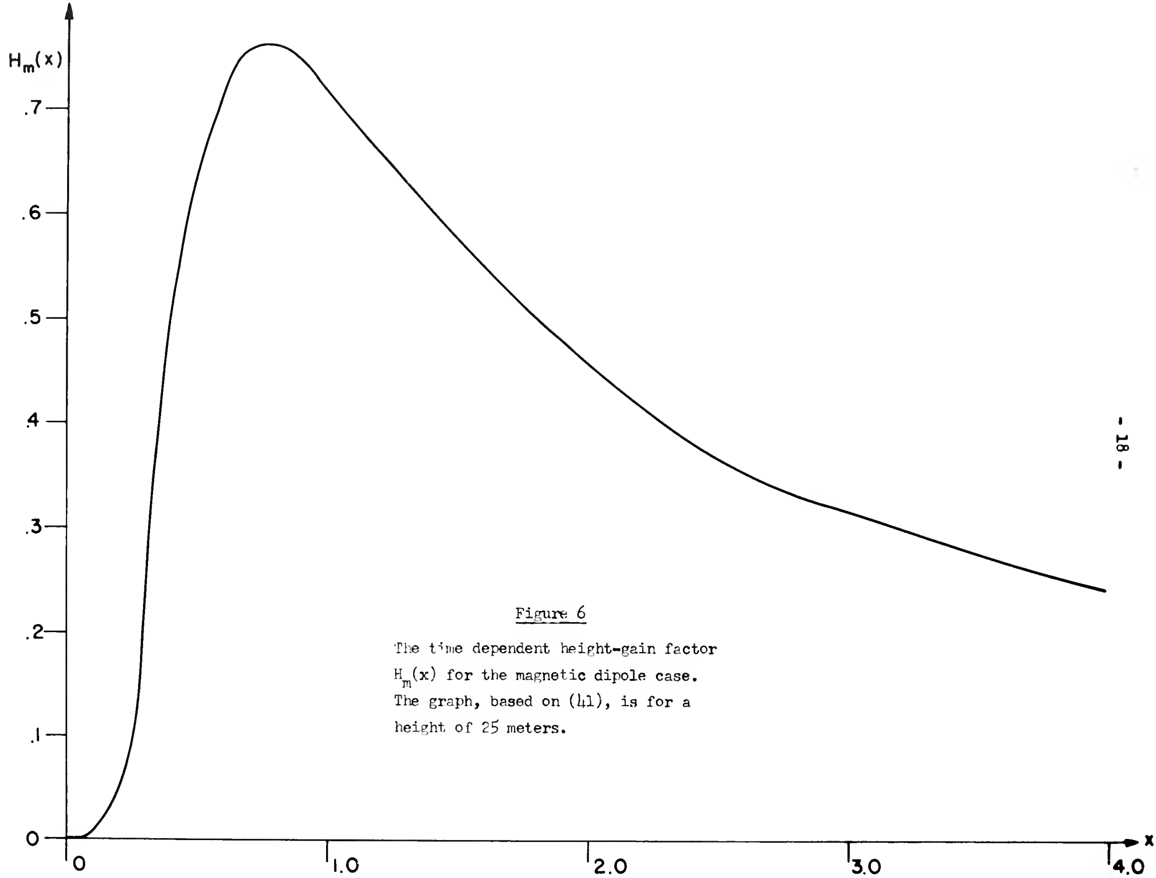


Figure 6

The time dependent height-gain factor $H_m(x)$ for the magnetic dipole case. The graph, based on (41), is for a height of 25 meters.

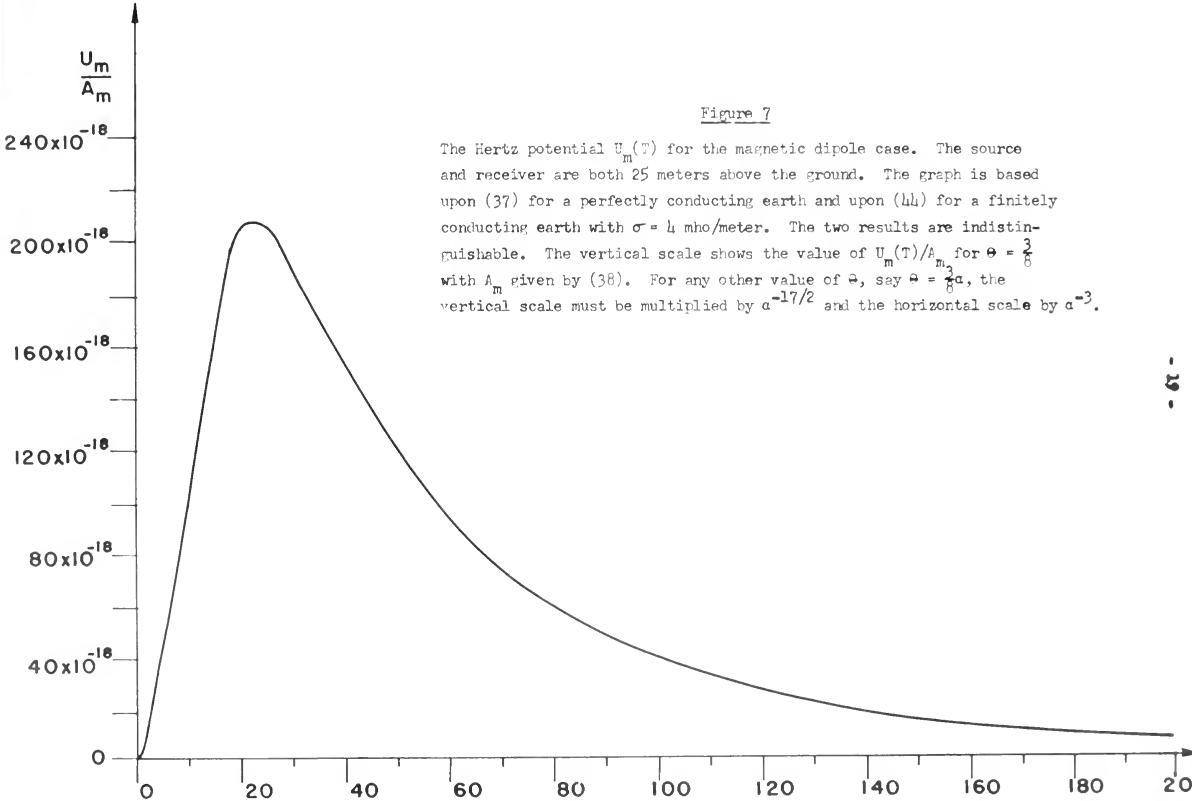


Figure 7

The Hertz potential $U_m(T)$ for the magnetic dipole case. The source and receiver are both 25 meters above the ground. The graph is based upon (37) for a perfectly conducting earth and upon (44) for a finitely conducting earth with $\sigma = 4$ mho/meter. The two results are indistinguishable. The vertical scale shows the value of $U_m(T)/A_m$ for $\theta = \frac{3}{8}$ with A_m given by (38). For any other value of θ, say $\theta = \frac{3}{8}\alpha$, the vertical scale must be multiplied by $\alpha^{-17/2}$ and the horizontal scale by α^{-3}.

DISTRIBUTION LIST FOR RESEARCH REPORTS

Contract No. AF 19(604)1717

(ONE copy unless otherwise noted)

Commander
Air Force Missile Test Center
Patrick Air Force Base, Florida
ATTN: Technical Library

Commander
Air Research and Development Command
Washington 25, D.C.
ATTN: RDDL

Commander
Air Research and Development Command
Washington 25, D.C.
ATTN: Lt. Col. R.F. Bowker, RDTDRC-1

Director
Air University Library
Maxwell Air Force Base, Alabama
ATTN: CR-4582

Headquarters, USAF
Director of Research and Development
Washington 25, D.C.
ATTN: AFDRD

Commander
Wright Air Development Center
Wright-Patterson Air Force Base, Ohio
ATTN: Mr. Walter J. Portune, WCLRS-6

Commander
Wright Air Development Center
Wright-Patterson Air Force Base, Ohio
ATTN: WCLNT-5, N. Draganjac

Commander
Wright Air Development Center
Wright-Patterson Air Force Base, Ohio
ATTN: WCLRE-5, Wave Prop. Section

Air Technical Intelligence Center
Wright-Patterson Air Force Base, Ohio
ATTN: AFOIN-4Bia

Commander
Rome Air Development Center
Griffiss Air Force Base
Rome, New York
ATTN: RCSST-3

Commander
Rome Air Development Center
Griffiss Air Force Base
Rome, New York
ATTN: RCERA-1, D. Mather

Commander
Rome Air Development Center
Griffiss Air Force Base
Rome, New York
ATTN: RCER, Dr. Burgess

Commander
Holloman Air Res. and Dev. Center
Holloman Air Force Base, New Mexico
ATTN: HDOI

Director
Evans Signal Laboratory
Belmar, New Jersey
ATTN: Mr. O.C. Woodyard

Director
Evans Signal Laboratory
Belmar, New Jersey
ATTN: Technical Document Center

Signal Corps Liaison Officer
Mass. Institute of Technology
Cambridge 39, Massachusetts
ATTN: A.D. Bedrosian

Commanding General
SC Engineering Laboratories
Fort Monmouth, New Jersey
ATTN: SCEL Technical Documents Center
Bay 2C122

Department of the Army
Office of the Chief Signal Officer
Washington 25, D.C.
ATTN: SIGRD

Department of the Army
Office of Chief Signal Officer
Engineering and Tech. Division
Washington 25, D.C.
ATTN: SIGNET-5

Director
Ballistics Research Laboratory
Aberdeen Proving Ground, Maryland
ATTN: Ballistics Measurement Lab.

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland
ATTN: Technical Information Branch
Victor W. Richard

Diamond Ordnance Fuze Laboratories
Washington 25, D.C.
ATTN: Guided Missile Fuze Library
R.D. Hatcher, Chief Microwave
Development Section

(10)Document Service Center
Armed Services Tech. Information Agency
Knott Building
Dayton 2, Ohio
ATTN: DSC-SC

Office of Technical Services
Department of Commerce
Washington 25, D.C.
ATTN: Tech. Reports Section

National Bureau of Standards
Department of Commerce
Washington 25, D.C.
ATTN: Dr. A.G. McNish

National Bureau of Standards
Department of Commerce
Washington 25, D.C.
ATTN: Gustave Shapiro

Boulder Laboratories Library
National Bureau of Standards
Boulder, Colorado
ATTN: Mrs. Victoria S. Barker, Lib.

Director
National Bureau of Standards
Central Radio Prop. Laboratory
Boulder, Colorado
ATTN: Division 14.0

Library
Division of Public Documents
U.S. Government Printing Office
Washington 25, D.C.

(2)Commander
Air Force Cambridge Research Center
Laurence G. Hanscom Field
Bedford, Mass.
ATTN: Electronics Document Room
CROOTR-2E

(3)Commander
Air Force Cambridge Research Center
Laurence G. Hanscom Field
Bedford, Mass.
ATTN: CRRD- R.E. Hiatt

(10)Commander
L.G. Hanscom Air Field
Bedford, Mass.
CROOTR-2

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D.C.
ATTN: Code Aer-TD-414

Chief, Bureau of Ships
Navy Department
Washington 25, D.C.
ATTN: Mr. E. Johnston, Code 838

Commander
U.S. Naval Air Missile Test Center
Point Mugu, California
ATTN: Code 366; MT-6

U.S. Naval Ordnance Laboratory
White Oak
Silver Spring 19, Maryland
ATTN: The Library

Commander
U.S. Naval Ordnance
Test Station (Code 753)
China Lake, California

Librarian
U.S. Naval Postgraduate School
Monterey, California

Director
U.S. Naval Research Laboratory
Washington 25, D.C.
ATTN: Code 1110

Director, National Security Agency
Washington 25, D.C.

Director
U.S. Naval Research Laboratory
Washington 25, D.C.
ATTN: Code 2021

Director
U.S. Naval Research Laboratory
Washington 25, D.C.
ATTN: Code 5250, J. Bohnert

Commanding Officer and Director
U.S. Navy Underwater Sound Lab.
Fort Trumbull, New London, Conn.
ATTN: Mr. C.M. Dunn

Chief of Naval Research
Navy Department
Washington 25, D.C.
ATTN: Code 427

(2)Commanding Officer and Director
U.S. Navy Electronics Lab. Lib.
San Diego 52, California

Chief, Bureau of Ordnance
Navy Department
Washington 25, D.C.
ATTN: Technical Library, Code Ad3
Mr. H.E. Rex, Code Re54

Chief, Bureau of Ordnance
Navy Department
Washington 25, D.C.
ATTN: Mr. C.H. Jackson, Code Re9a

Chief, Bureau of Ordnance
Navy Department
Washington 25, D.C.
ATTN: L.E. Wallingford, Code Re4f

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D.C.
ATTN: Code Aer-EL-931

Chief Bureau of Ships
Navy Department
Washington 25, D.C.
ATTN: L.E. Shoemaker, Code 838D

(2)Commander
U.S. Naval Air Development Center
Johnsville, Pennsylvania

Commander
U.S. Naval Air Test Center
Patuxent River, Maryland
ATTN: ET-315, Antenna Section

Naval Ordnance Laboratory
Corona, California
ATTN: Library

U.S. Naval Ordnance Laboratory
Department of the Navy
Corona, California
ATTN: Dr. Robert L. Conger

U.S. Naval Ordnance Plant
Indianapolis 18, Indiana
ATTN: AD-130 (Library)

Airborne Instruments Lab., Inc.
160 Old Country Road
Mineola, New York
ATTN: Librarian

ACF Electronics
800 N. Pitt Street
Alexandria, Pennsylvania
ATTN: Tech. Library

American Machine and Foundry Company
Electronics Division
1085 Commonwealth Avenue
Boston 15, Mass.
ATTN: Technical Library
Mrs. Rita Moravcsik, Librarian

Andrew Alford Consulting Engineers
299 Atlantic Avenue
Boston 10, Massachusetts
ATTN: Dr. A. Alford

Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio
ATTN: I-205 F -F
Dr. Bernard H. List

Bell Aircraft Corporation
P.O. Box 1
Buffalo 5, New York
ATTN: Technical Library
Mrs. Jasmine H. Mulcahey

Bell Telephone Labs., Inc.
Whippany, New Jersey
ATTN: Technical Information Lib.

Bendix Aviation Corporation
Pacific Division
11600 Sherman Way
North Hollywood, Calif.
ATTN: Technical Library
J.R. Breninger, Engr. Librarian

Bendix Radio
Div. of Bendix Aviation Corporation
East Joppa Road
Towson 4, Maryland
ATTN: Res. and Development Lab. (465)
Chief Engineer

Bjorksten Research Laboratories, Inc.
P.O. Box 265
Madison 1, Wisconsin
Attn: F.B. Korsgard, Treasurer

Boeing Airplane Company
Pilotless Aircraft Division
Seattle 14, Washington
ATTN: Pilotless Aircraft Div. Library
R.R. Barber, Library Supervisor

Boeing Airplane Company
Wichita Division
Wichita, Kansas
ATTN: Kenneth C. Knight, Librarian

Boeing Airplane Company
Seattle Division
Seattle 24, Washington
ATTN: E.T. Allen, Librarian

Chance Vought Aircraft, Inc.
P.O. Box 5907
Dallas, Texas
ATTN: Engineering Library
Mr. H.S. White, Librarian

Convair, A Division of General Dynamics Corp.
Fort Worth 1, Texas
ATTN: K.G. Brown, Div. Res. Librarian

Convair, Division of General Dynamics Corporation
San Diego 12, California
ATTN: Engineering Library

Cornell Aero. Laboratory, Inc.
4455 Genesee Street
Buffalo 21, New York
ATTN: Elma T. Evans, Librarian

Dalmo Victor Company
1414 El Camino Real
San Carlos, California
ATTN: Dorothea Quigley, Tech. Libr.

Dorne and Margolin, Inc.
30 Sylvester Street
Westbury, L.I., New York

Douglas Aircraft Company, Inc.
Long Beach Division
Long Beach 1, California
ATTN: Engineering Library (C-250)

Douglas Aircraft Company, Inc.
827 Lapham Street
El Segundo, California
ATTN: Engineering Library

Douglas Aircraft Company, Inc.
3000 Ocean Park Boulevard
Santa Monica, California
ATTN: Eq. Sec. Reference Files,
Eq. Eng. A250

Douglas Aircraft Corporation
Tulsa, Oklahoma
ATTN: Technical Library

Electronic Defense Laboratory
P.O. Box 205
Mountain View, California
ATTN: Library

Electronics Research, Inc.
2300 N. New York Avenue
Evansville, Indiana
ATTN: B.H. Baldridge,
Engineering Supervisor

Emerson and Cuming, Inc.
869 Washington Street
Canton, Mass.
ATTN: W.R. Cuming

The Emerson Electric Mfg. Company
8100 Florissant Avenue
St. Louis 21, Missouri
ATTN: Mr. E. Breslin,
Emerson Engineering Library

Fairchild Aircraft
Division Fairchild Eng. and Airplane Corp.
Hagerstown, Maryland
ATTN: Library

Farnsworth Electronics Company
Fort Wayne 1, Indiana
ATTN: Technical Library

Federal Telecommunication Labs.
500 Washington Avenue
Nutley 10, New Jersey
ATTN: Technical Library

Gabriel Electronics
Division Gabriel Company
Needham Heights, Mass.
ATTN: Miss Elaine Foss, Librarian

General Electric Company
Ithaca, New York
ATTN: Advanced Electronics Center
Library, John B. Travis

General Electric Company
Electronics Park
Syracuse, New York
ATTN: Mrs. Anne Damon, Documents
Librarian, Documents Lib.
Bldg. 3-143

General Precision Laboratory, Inc.
63 Bedford Road
Pleasantville, New York
ATTN: Mrs. Mary G. Herbst, Librarian

Goodyear Aircraft Corp.
1210 Massillon Road
Akron 15, Ohio
ATTN: Library D/120 Plant A

Grumman Aircraft Engineering Corp.
Bethpage, L.I., New York
ATTN: Engineering Library,
Plant No. 5

Hallicrafters Corporation
440 West 5th Avenue
Chicago, Illinois
ATTN: Library

Hoffman Laboratories, Inc.
Los Angeles, California
ATTN: Library

Hughes Aircraft Company
Microwave Laboratory
Culver City, California
ATTN: Library, Building 12
M.D. Adcock, Head, Antenna Dept.

Hughes Aircraft Company
Culver City, California
ATTN: Research and Development Lib.

Hycon Eastern, Inc.
75 Cambridge Parkway
Cambridge, Mass.
ATTN: Mr. S. Stein, Library

International Business Machines Corp.
Military Products Division
590 Madison Avenue
New York 22, New York
ATTN: Mr. C.F. McElwain

International Business Machines Corp.
Military Products Division
Airborne Computer Laboratories
Vestal, New York
ATTN: Mr. J.J. Walsh, Dept. 528

Jansky and Bailey, Inc.
1339 Wisconsin Avenue, N.W.
Washington, D.C.
ATTN: Tech. Library, Delmer C. Ports

Henry Jasik, Consulting Engineering
61 Second Street
Mineola, New York

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California
ATTN: I.E. Newlan

Martin Katzin and Co., Consultants
711 14th Street, N.W.
Washington 5, D.C.

Lincoln Laboratory
P.O. Box 73
Lexington 73, Massachusetts
ATTN: Henry Straus, Document Rm., A-229

Lockheed Aircraft Corporation
Missile Systems Division
7701 Woodley Avenue
Van Nuys, California
ATTN: MSD Library -902, Dept. 82-10
E.A. Blasi, Head, Antenna Lab.

Lockheed Aircraft Corporation
California Division
Engineering Library
Dept. 72-25, Plant A-1, Bldg. 63-1
ATTN: N.C. Harnois

The Glenn L. Martin Company
Denver, Colorado
ATTN: Wm. V. Foley, Engineering Lib.

The Glenn L. Martin Company
Baltimore 3, Maryland
ATTN: Engineering Library
Antenna Design Group

Maryland Electronic Mfg. Corp.
5009 Calvert Road
College Park, Maryland
ATTN: H. Warren Cooper

Mathematical Reviews
80 Waterman Street
Providence 6, Rhode Island

The W.L. Maxon Corporation
460 West 34th Street
New York, New York
ATTN: Antenna Laboratory

McDonnell Aircraft Corporation
Box 516
St. Louis 3, Missouri
ATTN: R.D. Detrich
Engineering Library

McMillan Laboratory, Inc.
Ipswich, Massachusetts
ATTN: Security Officer
Document Room

Melpar, Inc.
3000 Arlington Boulevard
Falls Church, Virginia
ATTN: Engineering, Technical Lib.

Microwave Radiation Company
19223 So. Hamilton Street
Gardena, California
ATTN: Mr. Morris J. Ehrlich, Pres.

Northrop Aircraft, Inc.
Engineering Department
1000 E. Broadway
Hawthorne, California
ATTN: E.A. Freitas, Engineering Library, Plant III

North American Aviation, Inc.
12214 Lakewood Boulevard
Downey, California
ATTN: Technical Library, Dept. 991-4

North American Aviation, Inc.
Los Angeles International Airport
Los Angeles 45, California
ATTN: Engineering Technical File

Page Communications Engineers
710 14th Street, N.W.
Washington 5, D.C.
ATTN: Library

Philco Corporation Research Division
A and Lippincott Street
Philadelphia 34, Pa.
ATTN: Technical Library

Pickard and Burns, Inc.
240 Highland Avenue
Needham 94, Mass.
ATTN: Dr. J.T. de Bettencourt

Polytechnic Research and Development Company, Inc.
202 Tillary Street
Brooklyn 1, New York
ATTN: Technical Library

Radiation Engineering Laboratory
Maynard, Mass.
ATTN: Dr. John Ruze

Radiation, Inc.
P.O. Drawer 37
Melbourne, Florida
ATTN: Technical Library
Mr. M.L. Cox, Assistant Project Engineer

Radio Corp. of America
RCA Laboratories
Rocky Point, New York
ATTN: P.S. Carter, Lab. Library

RCA Laboratories
Princeton, New Jersey
ATTN: Miss Fern Cloak, Librarian
Research Library

RCA Defense Electronic Products
Camden 2, New Jersey
ATTN: Miss J.M. Steever, Librarian
Library 10-2

(2)The Ramo-Wooldridge Corporation
5730 Arbor Vitae Street
Los Angeles 45, California
ATTN: Margaret C. Whitnah, Chief Librarian, Research and Development Library

The Rand Corporation
Via: SBAMA Liaison Office
1700 Main Street
Santa Monica, California
ATTN: Library

Rantic Corporation
Carlabasos, California
ATTN: Technical Library

Raytheon Manufacturing Company
M and R Division
Bedford, Massachusetts
ATTN: Irving Goldstein

Raytheon Laboratory
Wayland, Massachusetts
ATTN: Document Lib., John E. Walsh
Dept. 8974, Antenna

Raytheon Manufacturing Company
Wayland Laboratory
Wayland, Massachusetts
ATTN: Miss Alice G. Anderson, Lib.
Wayland Library

Republic Aviation Corporation
Farmingdale, L.I., New York
ATTN: H. Stieglitz, Engineering Lib.

Rheem Manufacturing Company
Research and Development
9236 East Hall Road
Downey, California
ATTN: J.C. Joerger

Ryan Aeronautical Company
San Diego, California
ATTN: Technical Library

Sanders Associates
137 Canal Street
Nashua, New Hampshire
ATTN: N.R. Wild, Library

Sandia Corporation
P.O. Box 5800
Classified Document Division
Albuquerque, New Mexico

Sperry Gyroscope Company
Great Neck, L.I., New York
ATTN: Engineering Library
Florence W. Turnbull, Engr. Librarian

Stanford Research Institute
Menlo Park, California
ATTN: Engineering Document Library
Mrs. Beatrice Gibson, Libr.

Sylvania Electric Company
100 First Street
Waltham, Mass.
ATT: Librarian

Systems Laboratories Corporation
15016 Ventura Blvd.
Sherman Oaks, California
ATTN: Dr. W.C. Hoffman

Technical Research Group
17 Union Square West
New York 3, New York

A.S. Thomas, Inc.
161 Devonshire Street
Boston, Mass.
ATTN: A.S. Thomas

Westinghouse Electric Corp.
2519 Wilkens Avenue
Baltimore 3, Maryland
ATTN: Engineering Library
Kent M. Mack

Wheeler Laboratories, Inc.
122 Cutter Mill Road
Great Neck, New York
ATTN: Mr. Harold A. Wheeler

Zenith Plastics Company
Box 91
Gardena, California
ATTN: Mr. S.S. Oleesky

Library
Geophysical Institute
University of Alaska
College, Alaska

Electronic Research Laboratory
Div. of Electronic Engineering
University of California
Berkeley 4, California
ATTN: S. Silver

Electronics Research Laboratory
232 Cory Hall
University of California
Berkeley 4, California
ATTN: J.R. Whinnery

California Institute of Technology
1201 E. California Street
Pasadena, California
ATTN: Dr. Charles H. Papas

Carnegie Institute of Technology
Pittsburgh 13, Pennsylvania
ATTN: Albert E. Heins

School of Electrical Engineering
Cornell University
Ithaca, New York
ATTN: Dr. Henry G. Booker

College of Engineering
University of Florida
Gainesville, Florida
ATTN: Engineering Sciences Library
Professor M.H. Latour

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia
ATTN: Georgia Tech. Library
Mrs. J.H. Crosland

Technical Reports Collection
Harvard University
Gordon McKay Library
303A Pierce Hall
Oxford Street
Cambridge 38, Massachusetts
ATTN: Mrs. E.L. Hufschmidt, Librarian

Harvard College Observatory
60 Garden Street
Cambridge, Massachusetts
ATTN: Dr. Fred L. Whipple

Serials Department -220-S Library
University of Illinois
Urbana, Illinois
ATTN: Engineering Library

Antenna Section
Electrical Engr. Research Laboratory
University of Illinois
Urbana, Illinois
ATTN: EERL Library, Room 210,
Dr. R.H. DuHamel

The Johns Hopkins University
Department of Physics
Baltimore 18, Maryland
ATTN: Professor Donald E. Kerr

Radiation Laboratory
Johns Hopkins University
1315 St. Paul Street
Baltimore 2, Maryland

Applied Physics Laboratory
The Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland
ATTN: Document Library

Massachusetts Institute of Technology
Research Laboratory of Electronics
Document Room 20B-221
Cambridge 39, Massachusetts

University of Michigan
Electronic Defense Group
Engineering Research Institute
Ann Arbor, Michigan
ATTN: J.A. Boyd, Supervisor

Willow Run Labs., of the Engineering Research Institute
The University of Michigan
Willow Run Airport
Ypsilanti, Michigan
ATTN: K.M. Siegel, Head, Theory and Analysis Department

University of Michigan
Willow Run Laboratories
Willow Run Airport
Ypsilanti, Michigan
ATTN: Shelia Coon, Librarian

University of Minnesota
Minneapolis, Minnesota
Engineering Library
ATTN: Head Librarian

Microwave Laboratory
Electrical Engineering Dept.
Northwestern University
Evanston, Illinois
ATTN: Prof. R.E. Beam

Antenna Laboratory
Department of Electrical Engineering
Ohio State University
Columbus, Ohio
ATTN: Dr. T.E. Tice

Oklahoma University Research Found.
Norman, Oklahoma
ATTN: Technical Library
Professor C.L. Farrar

Microwave Research Institute
55 Johnson Street
Brooklyn 1, New York
ATTN: Dr. A.A. Oliner

Polytechnic Institute of Brooklyn
55 Johnson Street
Brooklyn 1, New York
ATTN: Microwave Research Institute

Syracuse University
Dept. of Electrical Engr.
Syracuse 10, New York
ATTN: Technical Library

University of Texas
Electrical Engr. Research Lab.
P.O. Box 8026, Univ. Station
Austin 12, Texas
ATTN: John R. Gerhardt

Dept. of Physics
University of Texas
Austin 12, Texas
ATTN: Physics Library
Claude W. Horton

Tufts University
Medford 55, Massachusetts
ATTN: Research Lab. of Physical Electronics
Professor Charles R. Mingins

University of Toronto
Dept. of Electrical Engineering
Toronto, Ontario, Canada
ATTN: Prof. George Sinclair

University of Washington
Dept. of Electrical Engineering
Seattle, Washington
ATTN: Prof. G. Held

Ionosphere Research Laboratory
Pennsylvania State College
State College, Pennsylvania
ATTN: Prof. A.H. Waynick, Director

Institute of Mathematical Science
25 Waverly Place
New York 3, New York
ATTN: Mrs. JoAn Segal, Librarian

School of Electrical Engineering
Purdue University
Lafayette, Indiana
ATTN: Professor F.V. Schultz

Department of Electrical Engineering
California Institute of Technology
ATTN: Dr. Charles H. Papas

Electronics Division
Rand Corporation
1700 Main Street
Santa Monica, California
ATTN: Dr. Robert Kalaba

National Bureau of Standards
Washington, D.C.
ATTN: Dr. W.K. Saunders

Applied Mathematics and Statistics Lab.
Stanford University
Stanford, California
ATTN: Dr. Albert H. Bowker

Department of Physics and Astronomy
Michigan State University
East Lansing, Michigan
ATTN: Dr. A. Leitner

University of Tennessee
Knoxville, Tennessee
ATTN: Dr. Fred A. Ficken

California Institute of Technology
1201 E. California Street
Pasadena, California
ATTN: Dr. A. Erdelyi

Wayne University
Detroit, Michigan
ATTN: Professor A.F. Stevenson

Mathematics Department
Stanford University
Stanford, California
ATTN: Dr. Harold Levine

University of Minnesota
Minneapolis 14, Minnesota
ATTN: Prof. Paul C. Rosenbloom

Department of Mathematics
University of Pennsylvania
Philadelphia 4, Pa.
ATTN: Professor Bernard Epstein

Applied Physics Laboratory
The Johns Hopkins University
8621 Georgia Avenue
Silver Spring, Maryland
ATTN: Dr. B.S. Gouray

(2) Exchange and Gift Division
The Library of Congress
Washington 25, D.C.

Electrical Engineering Department
Massachusetts Institute of Tech.
Cambridge 39, Massachusetts
ATTN: Dr. L.J. Chu

Nuclear Development Assoc. Inc.
5 New Street
White Plains, New York
ATTN: Library

Lebanon Valley College
Annville, Pennsylvania
ATTN: Professor B.H. Bissinger

Dept. of Physics, Thaw Hall
University of Pittsburgh
Pittsburgh 13, Pa.
ATTN: Dr. Edward Gerjuoy

Dept. of Physics
Amherst College
Amherst, Massachusetts
ATTN: Dr. Arnold Arons

California Institute of Tech.
Electrical Engineering
Pasadena, California
ATTN: Dr. Zohrab A. Kaprielian

Dr. Rodman Doll
209A Emmet St.
Ypsilanti, Michigan

California Institute of Tech.
Pasadena 4, California
ATTN: Mr. Calvin Wilcox

(3) Mr. Robert Brockhurst
Woods Hole Oceanographic Inst.
Woods Hole, Massachusetts

National Bureau of Standards
Boulder, Colorado
ATTN: Dr. R. Gallet

Engineering Library
Plant 5
Grumman Aircraft Corp.
Bethpage, L.I., New York
ATTN: Mrs. A.M. Gray

Mrs. Jane Scanlon
284 South Street
Southbridge, Massachusetts

Dr. Solomon L. Schwebel
3689 Louis Road
Palo Alto, California

Microwave Laboratory
55 Johnson Street
Brooklyn, New York
ATTN: Dr. Bernard Lippmann

University of Minnesota
The University Library
Minneapolis 14, Minnesota
ATTN: Exchange Division

Professor Bernard Friedman
55 Hilltop Avenue
New Rochelle, New York

Lincoln Laboratory
Massachusetts Institute of Tech.
P.O. Box 73
Lexington 73, Mass.
ATTN: Dr. Shou Chin Wang, Rm. C-351

Melpar, Inc.
3000 Arlington Boulevard
Falls Church, Virginia
ATTN: Mr. K.S. Kelleher, Section Head

Antenna Laboratory, ERL
HQ Air Force Cambridge Research Center
Laurence G. Hanscom Field
Bedford, Massachusetts
ATTN: Nelson A. Logan

Electronics Research Directorate
HQ Air Force Cambridge Research Center
Laurence G. Hanscom Field
Bedford, Massachusetts
ATTN: Dr. Philip Newman, CRRK

HQ Air Force Cambridge Research Center
Laurence G. Hanscom Field
Bedford, Massachusetts
ATTN: Mr. Francis J. Zucker

Crosley AVCO Research Labs.
257 Crescent Street
Waltham, Massachusetts
ATTN: Mr. N.C. Gerson

Antenna Research Section
Microwave Laboratory
Hughes Aircraft Company
Culver City, California
ATTN: Dr. Richard B. Barrar

Columbia University
Hudson Laboratories
P.O. Box 239
145 Palisade Street
Dobbs Ferry, New York
ATTN: Dr. M.W. Johnson

Institute of Fluid Dynamics and Applied Math.
University of Maryland
College Park, Maryland
ATTN: Dr. Elliott Montroll

Dept. of Electrical Engineering
Washington University
Saint Louis 5, Missouri
ATTN: Professor J. Van Bladel

Dept. of the Navy
Office of Naval Research Branch Office
1030 E. Green Street
Pasadena 1, California

Brandeis University
Waltham, Massachusetts
ATTN: Library

General Electric Company
Microwave Laboratory
Electronics Division
Stanford Industrial Park
Palo Alto, California
ATTN: Library

Hughes Research Laboratories
Hughes Aircraft Company
Culver City, California
ATTN: Dr. W.A. Eclid
Bldg. 12, Rm. 2529

Smyth Research Associates
3930 4th Avenue
San Diego 3, California
ATTN: Dr. John B. Smyth

Electrical Engineering
California Institute of Tech.
Pasadena, California
ATTN: Dr. Georges G. Weill

Naval Research Laboratory
Washington 25, D.C.
ATTN: Dr. Henry J. Passerini
Code 5278 A

Dr. George Kear
10585 N. Stelling Rd.
Cupertino, California

Brooklyn Polytechnic Institute
85 Livingston Street
Brooklyn, New York
ATTN: Dr. Nathan Marcuvitz

Department of Electrical Engr.
Brooklyn Polytechnic Institute
85 Livingston Street
Brooklyn, New York
ATTN: Dr. Jerry Shmoys

Dept. of Mathematics
University of New Mexico
Albuquerque, New Mexico
ATTN: Dr. I. Kolodner

W.L. Maxon
460 W. 34th Street
New York, N.Y.
ATTN: Dr. Harry Hochstadt

NYU
EM-
102 Levy

Propagation of electromag-
netic pulses around the
earth.